Detecting the Transition From Pop III to Pop II Stars

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Abstract

We discuss the cosmological significance of the transition from the Pop III to Pop II mode of star formation in the early universe, and when and how it may occur in primordial galaxies. Observations that could detect this transition include those of element abundances in metal-poor Galactic halo stars, and of the helium reionization and associated heating of the intergalactic medium. We suggest that gamma-ray bursts may be a better probe of the end of the first-stars epoch than of Pop III stars.

Key words: cosmology, theory, Population III stars, cosmic microwave background, reionization, intergalactic medium, gamma ray burst

1 The End of the First Stars Epoch: A Cosmic Milestone

The nature of the primordial stellar initial mass function (IMF) is currently a problem of great interest. Some recent theoretical work indicates that this IMF may have been top-heavy (Abel et al., 2000; Bromm et al., 2002), leading predominantly to stellar masses $\geq 100\ M_\odot$ up to a critical gas metallicity, $Z_{\rm cr} \approx 10^{-4\pm1} Z_\odot$ (Bromm et al., 2001a; Schneider et al., 2002), above which a present-day IMF occurs. However, other detailed studies of stellar feedback on accreting matter (Tan & McKee, 2004) and of the current data on reionization and the metal abundance ratios in extremely metal-poor (EMP) Galactic halo stars (Tumlinson et al., 2004) suggest otherwise: that the primordial IMF, rather than being biased towards high masses, may merely lack low-mass stars. The transition metallicity $Z_{\rm cr}$ may be significantly higher at low densities and could vary with metal species such as C, O and Fe which are important coolants in metal-free gas (Bromm & Loeb, 2003; Santoro & Shull, 2005).

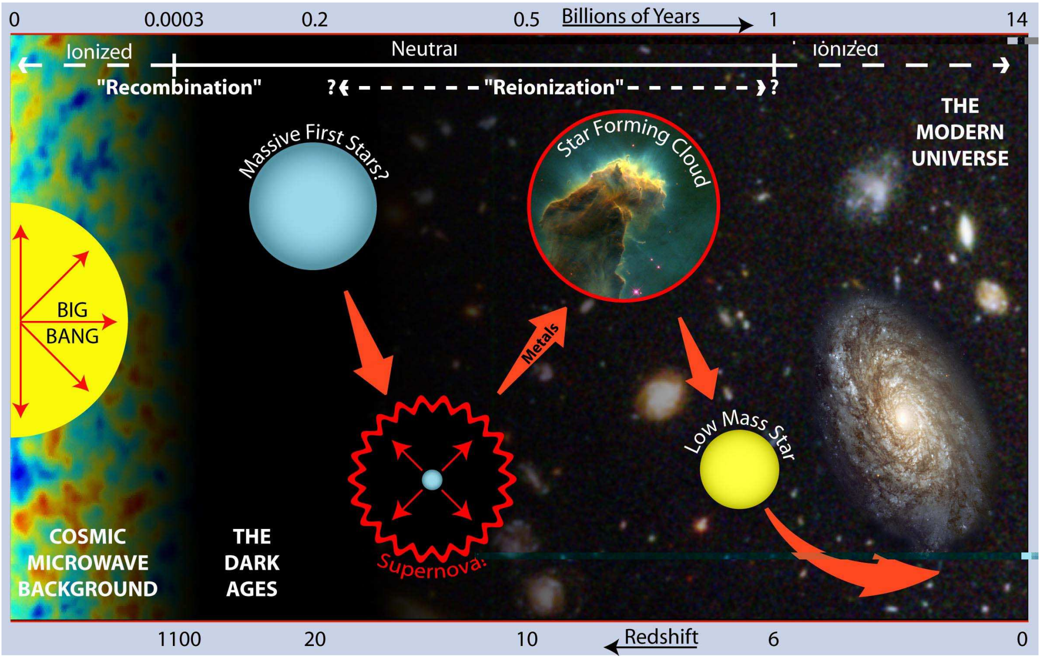

Fig. 1. A schematic representation of the transition at early cosmological epochs from the first metal-free stars to second-generation star formation, following the generation of metals from the first SNe. The H and He reionization of the IGM may be completed by early stellar generations prior to the epochs of massive QSOs at $z < 6$, with partial or complete recombination during the metallicity transition phase. In this case, a second reionization of H at $z \sim 6$ and of He at $z \sim 3$ subsequently occur.

Stars of masses $\sim$ 10–100 $M_\odot$ end their lives as the more familiar Type II supernovae (SNe), leaving behind neutron stars and black holes, whereas metal-free stars in the mass range $\sim$ 140–260 $M_\odot$ are thought to disrupt themselves entirely as pair-instability SNe (PISNe). A first-stars metal-free IMF spanning stellar masses 10–140 $M_\odot$ is fully consistent with the current data on reionization – including the enhanced electron-scattering optical depth, $\tau_e \sim$ 10–15% in the cosmic microwave background (CMB) – and on nucleosynthetic abundances in EMP stars (Tumlinson et al., 2004), the intergalactic medium (IGM; Venkatesan & Truran 2003), and in QSO broad-emission-line regions at high redshifts, z (Venkatesan et al., 2004). This requires metal-free star formation (SF) to last for $\sim 10^7$–10^8 yr in early galactic halos, which is entirely consistent with calculations on the duration of the Pop III epoch from semi-analytic (Tumlinson et al., 2004) and numerical methods (Wada & Venkatesan, 2003; Bromm et al., 2003). Since the transport of metals and radiation in primordial galaxies and the IGM is almost certain to be highly inhomogeneous, the transition from a Pop III (metal-free first stars) to Pop II (second-generation metal-poor) IMF, illustrated in Figure 1, may vary significantly in space and time. The onset of Pop II SF may be non-unique cosmologically, rather than an abrupt global transition.

Regardless of the uncertainties related to the primordial stellar IMF and the transition epochs to Pop II SF, we expect the first generations of stars to form from metal-free gas. Their composition heavily influences their structure and properties, as they rely predominantly on the p–p chain initially than on the more efficient CNO cycle for their thermonuclear fuel source (Tumlinson et al., 2003). Consequently, metal-free stars are hotter and emit significantly harder ionizing radiation relative to their finite-Z counterparts (Bromm et al., 2001b; Tumlinson et al., 2003; Schaerer, 2002). Thus, the traditional distinction between the hard ionizing spectra of QSOs and the relatively soft spectra of stars fails in the case of Pop III SF. This has critical consequences for several problems in cosmology, as we detail below.

Last, we note that gas transition metallicities of $Z_{\rm cr} \sim 10^{-3.5} Z_{\odot}$ mark a genuine milestone in cosmic history. Using current stellar evolution models, we can derive that the minimum number of ionizing photons per baryon that must have been generated in association with this value of $Z_{\rm cr}$ (whether in total Z, or individual metals) is at least 1–10 (Venkatesan & Truran, 2003). This is because metal free stars in a present day IMF are 10–20 times more efficient at generating ionizing radiation per metal yield than are solar-Z stars (Schaerer, 2002; Venkatesan & Truran, 2003). Therefore, the universe may well have been reionized by the time $Z_{\rm cr}$ is achieved in individual halos or the IGM, an important potential feature of the cosmic backdrop in which Pop II SF commences.

2 Constraints from the CMB

The 1-year temperature-polarization correlation data of the CMB from $WMAP$ implies a large Thomson optical depth of $\tau_e \sim 0.17 \pm 0.08$ (Spergel et al., 2003). In a single-step reionization scenario, where the IGM abruptly transitions from being neutral to completely ionized, this translates to a reionization epoch, $z_{\rm reion} \sim 17 \pm 4$. At first glance, this is not compatible with Gunn-Peterson (GP) studies of the high-z IGM, which indicate $z_{\rm reion} \sim 6$ (Venkatesan et al. 2003 and references therein). This raises the possibility of multiple reionizations or extended periods of partial ionization of H and/or He over $z \sim$ 6–20 (Venkatesan et al., 2003; Cen, 2003). As we emphasized earlier, a non-exotic stellar IMF consisting of metal-free stars in the mass range 10–140 $M_{\odot}$ can lead to values of $\tau_e \sim$ 0.1–0.15 (Tumlinson et al., 2004). We must also consider the additional contributions from X-rays from the first stars and QSOs (Venkatesan et al., 2001; Ricotti & Ostriker, 2004) and from He reionization, each of which may contribute a few percent. One possible method to disentangle these two differing contributions to τ_e in the CMB is to utilize future data at radio wavelengths in combination with the CMB to constrain the topology of reionization (see, e.g., S. Furlanetto, this proceedings). The far-UV He-

ionizing photons would be stopped close to the halos in sharp I-fronts which slowly advance into the IGM, whereas X-ray ionization would resemble fuzzy halos around the host galaxy, owing to the high penetrating power of X-rays.

We note that GP and CMB constraints are not necessarily incompatible when we consider that these techniques are sensitive to complementary stages of reionization. The first best probes trace amounts of neutral matter in the IGM whereas CMB photons experience the most scattering with IGM electrons during a sharp rise of IGM ionization. Furthermore, τ_e is only a cumulative measure whose values can be reproduced by a number of reionization histories. We suggest therefore that future measurements of CMB polarization, from *WMAP* or ground-based experiments, in combination with direct imaging of primordial stellar clusters may provide the best use of CMB data to constrain the transition from Pop III to Pop II SF at high redshifts.

3 The Role of Helium

As emphasized earlier, the first metal-free stars are significantly hotter and emit harder ionizing radiation than do low-Z stars of the same mass. Specifically, a $Z = 0$ stellar cluster creates 60% more H-ionizing photons and 10^5 more He-ionizing photons than a Pop II $Z = 0.001$ cluster in a Salpeter IMF over 1–100 $M_\odot$ (Venkatesan et al., 2003). This could lead to one or more reionization epochs for both H and He, boosting the IGM electron fraction and the detected τ_e in the CMB. The Thomson optical depth depends on the line-of-sight integral of the number density of electrons, n_e, which for a fully reionized IGM becomes, $n_e = n_{\rm H} + 2n_{\rm He}$. For $\frac{n_{\rm He}}{n_{\rm H}} = 0.08$, we see that complete He reionization can increase τ_e in the CMB up to an extra 16% of its value from H reionization alone, a small but significant contribution. The end of Pop III SF will lead to a loss of He-ionizing radiation and likely cause recombination of He III in the IGM. The accompanying emission of 4 Ryd photons and the consequent heating of the IGM may be detected through the thermal evolution of the IGM down to $z \sim 3$ (Hui & Haiman, 2003). Thus, the onset of Pop II star formation could be tracked through the He reionization and thermal history of the IGM.

An important factor in determining the evolution of H and He I-fronts and the geometry of ionized bubbles in primordial galaxies is the frequency dependence of the source spectrum. For a source whose specific intensity (erg s^{-1} Hz^{-1}) goes as $F_\nu \propto \nu^{-\alpha}$, we find that the ratio of photoionization rates per atom for He and H, R, is :

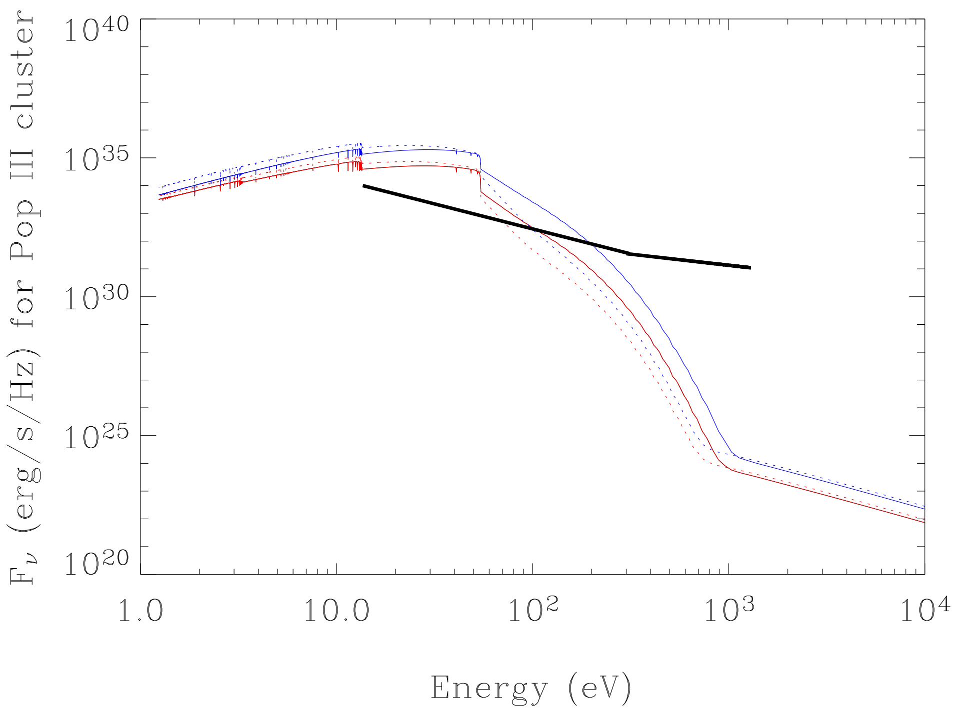

Fig. 2. The specific intensity as a function of energy of a fiducial 10^6 $M_\odot$ metal-free stellar cluster, based on Tumlinson et al. (2004). Solid and dashed lines denote the values on the ZAMS and at times of 2 Myr; within each of these cases, upper and lower lines represent 1–100 $M_\odot$ and 10–140 $M_\odot$ IMFs. Note the relative flatness (hardness) of the cluster's radiation between the H and He ionizing thresholds at 13.6 eV and 54.4 eV respectively, and the rapid decline of the He ionizing flux with time. For comparison, a typical QSO spectrum (arbitrarily normalized) with slopes 1.8 and 0.8 in the energy ranges 13.6–300 eV and $\geq$ 300 eV is also shown.

$$R \equiv \frac{Q(\mathrm{HeII})/n_{\mathrm{He}}}{Q(\mathrm{HI})/n_{\mathrm{H}}} = \left[\frac{\int_{4\mathrm{Ryd}}^{\infty} d\nu F_\nu/(h\nu)}{\int_{1\mathrm{Ryd}}^{\infty} d\nu F_\nu/(h\nu)}\right] \frac{n_{\mathrm{H}}}{n_{\mathrm{He}}} \tag{1}$$

For $\Omega_b h^2 = 0.0224$ and $y = n_{\mathrm{He}}/n_{\mathrm{H}} = 0.08$, the above ratio is unity when $\alpha_{\mathrm{crit}} \sim 1.82$. This is the critical spectral index at which the rate of H and He photoionizations become equal; for a sufficiently hard source, the He and H I-fronts may begin to coincide. Current calculations (Venkatesan & Shull, 2005) indicate that Pop III stars in a Salpeter slope 1–100 $M_\odot$ or 10–140 $M_\odot$ IMF may be unable to achieve this criterion ($R \geq 1$), especially when evolutionary effects are taken into account. This is shown in Figure 2, where we display the specific intensity of a fiducial $10^6 M_\odot$ Pop III cluster as a function of energy for these two IMFs. A numerical evaluation of R for these cases reveals that it never exceeds unity, mostly due to the sharp falloff of the intensity beyond the He II ionization threshold. However, a halo that hosts a QSO (also shown

in Figure 2) in addition to Pop III stars could well result in He and H I-fronts that advance together spatially.

As noted in Venkatesan et al. (2003), future data from, e.g., the *Cosmic Origins Spectrograph* on the *Hubble Space Telescope*, on the He II GP effect at $z > 3$ can place limits on relic ionization from Pop III stars, particularly in underdense regions of the IGM that may not have recombined after the Pop III era. Such data can also constrain the topology of escaping He-ionizing radiation and the relative roles of ionization from hard (Pop III stars and QSOs) and soft (Pop II stars) sources.

4 Dust Transport and Pop II Metallicities

Studies of EMP stars in the Galactic halo provide an excellent avenue complementary to those detailed above for probing the transition from Pop III to Pop II SF. Surviving members of low-mass second-generation stellar populations that form in the cooling shells of Pop III SN remnants (SNRs) may be detected as EMP stars at present. A large number of elements have been detected in many EMP stars, and their relative abundance ratios provide strong constraints on the IMF, formation conditions and chemical environment of early stellar generations. We present here some recent results on the role of dust transport in the segregated metal enhancement of Pop II starforming sites, and refer the interested reader to Tumlinson et al. (2004) for a detailed analysis of the current nucleosynthetic data on EMP stars and related limits on the first-stars IMF.

In Venkatesan et al. (2005), we investigated the radiative transport of dust within SNRs in primordial galaxies, motivated by the strong overabundances of the elements Mg, Si, O and C at low iron abundances in EMP stars. These trends are not easily explained by energetic Type II SN models alone. We consider a dust transport scenario involving graphite, silicate and iron-bearing magnetite grains, the dominant products of PISNe and metal-free Type II SNe. We include the effects of radiation pressure from Pop III stars, gravity, gas drag, grain charging, and sputtering on grain dynamics, and require only Pop III cluster luminosities of $\sim 10^6 L_\odot$ over timescales of 10^5 yr, and SN kinetic energies of at least 10^{51} erg. We find, for reasonable parameter assumptions, that the transport of the primary dust compounds within early SNRs can be segregated, leading to a differential accumulation of metals that seed Pop II SF in SN shells. The results from Venkatesan et al. (2005) can at least partly account for the element trends observed in C- and silicate-rich Fe-poor EMP stars, whose abundances are best explained in our models by a Pop III IMF over masses $\sim$ 10–150 $M_\odot$, as displayed in Figure 3.

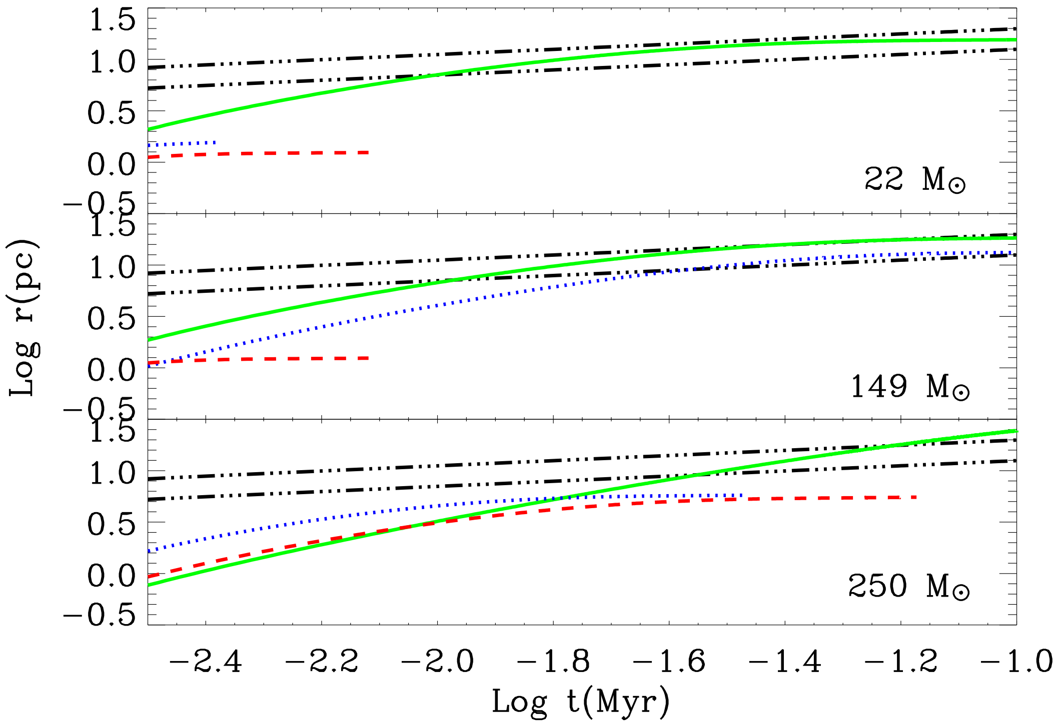

Fig. 3. The positions of dust grains within SNRs in primordial galaxies are shown as a function of time as they are radiatively transported outward from the center of the SNR. Top, middle and bottom panels represent stellar masses of 22 $M_{\odot}$, 149 $M_{\odot}$, and 250 $M_{\odot}$. Solid, dotted and dashed curves refer to graphites, silicates and magnetite grains. The two long dashed lines in each panel describe the adiabatic evolution of the SN shell radius, for $E_{\rm SN} = 10^{52}$ erg and and ambient gas number densities of 1 cm^{-3} (upper line) and 10 cm^{-3} (lower line).

5 Gamma-Ray Bursts From Pop III Stars?

In concluding our discussion of detecting Pop III and Pop II stars at high redshifts, we briefly examine the viability of constraining the first-stars epoch through gamma-ray bursts (GRBs). Many authors have proposed that GRBs associated with Pop III stars could be the most effective way to probe high-z SF, IGM ionization and metallicity at $z \geq 6$ (see, e.g., D. Lamb, this proceedings). At these redshifts, emission lines from QSOs and galaxies will become increasingly hard to detect owing to natural dimming with distance and absorption by the neutral IGM, whereas GRB afterglows experience a fortuitous near-constancy of spectral flux in an observed frequency range with increasing redshift. The association of GRBs with metal-free stars is largely theoretical at present; the observational evidence rests primarily on the GRB-SN association at low redshifts. The leading models for the long- and short-duration GRBs are respectively (Hurley, 2003) the single progenitor model, involving the core collapse of a massive star through a SN event, and binary models involving neutron stars and black holes. Let us examine these in turn.

First, the massive star model has been tested through the low-z detections of GRBs in association with metal-poor SNe of energies $\sim 10^{51}$–10^{53} erg. However, these SNe are also observed to be Type Ib/c in nature, i.e., lacking in hydrogen and/or helium envelopes. The Pop II progenitors of these objects have likely experienced significant mass loss, a critical factor for the success of the GRB mechanism. We may then question whether extending such low-z analogues to Pop III stars is appropriate or realistic, and whether the GRB engine can operate in the core of a compact Pop III star. After all, metal-free stars are essentially composed of a H/He envelope in their entirety! Second, the shortest timescales on which a short-duration GRB may form is of order 10 Myr from a high-mass binary system. We recall that on this timescale, an individual halo may well have experienced metal self-pollution that is sufficient to halt further Pop III SF. A GRB created in a binary scenario may then provide excellent constraints on the transition metallicity at which second-generation SF occurs in high-z halos. This problem clearly deserves more detailed investigation as well as more data on the GRB-SN connection. For now, we tentatively suggest that GRBs may in reality be a better probe of the *end* of the first-stars phase and the onset of Pop II SF.

6 Discussion

We have presented recent work that places limits on the IMF, epochs and formation conditions of Pop III and Pop II SF from a variety of data. The ideal method to test the predictions of these calculations would clearly be through direct detections of Pop III and/or Pop II stellar clusters at $z \geq 6$, through emission-line (He II, Lyα) and color signatures (Tumlinson et al. 2003, Rhoads & Malhotra, this proceedings). The viability of such detections depends strongly on the converse problem to the impact of Pop III stars on reionization, which is the effective trapping of radiation within primordial galaxies. A related theoretical goal is to better understand the duration of Pop III SF and the chemical feedback from the first SNe in driving the transition to Pop II SF: how quickly is the environment to form Pop III stars lost and is this a highly nonuniform process spatially and temporally? What are the timescales for halo self-enrichment versus pollution of neighboring galaxies? What are the metallicities of second-generation stars forming in the wake of the first SNe? These questions have a direct impact on the cosmological relevance of metal-free stars and on the planning of future missions that are explicitly designed to detect "First Light" such as the *James Webb Space Telescope*. We have attempted here to address some of these issues. Further theoretical progress in this field may depend on numerical simulations which are best suited to study problems such as these, whose nature inherently involves inhomogeneity and complex local feedback processes.

Other techniques to constrain the Pop III epochs and the transition to Pop II SF include the detection of GRBs, and of the near-IR and radio signals from early stellar sources as discussed by other authors in this volume. The discovery of a metal-free star in the local universe would also be an important stride towards understanding Pop III SF. This is however an exceedingly difficult observation in practice – as we mentioned in our talk, detecting the most iron-poor star currently known, a 1 part in 10^9 detection, is already equivalent to finding the author of this contribution in all of India! Until direct detections of a truly metal-free star become possible, indirect inferences must be made from the IGM reionization of H *and* He, the metal content of high-z systems, and stellar fossils in our Galactic backyard. Of these, EMP stars which could be survivors of the transition epochs from Pop III to II SF are likely the most fruitful avenue to constrain this problem in the near future.

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